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INVESTIGATION OF WELDED INTERCONNECTION OF LARGE AREA WRAPAROUND CONTACTED SILICON SOLAR CELLS

JPL CONTRACT NO. 956020

DAN R. LOTT

AUGUST 1984

FINAL REPORT

This work was performed for the Jet Propulsion
Laboratory, California Institute of Technology,
and the NASA Lewis Research Center through an
agreement with the National Aeronautics and
Space Administration.

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ABSTRACT

Lockheed Missiles & Space Company, Inc. has conducted an investigation to evaluate the welding and temperature cycle testing of large area 5.9 x 5.9 wraparound silicon solar cells utilizing printed circuit substrates with SSC-155 interconnect copper metals and the LMSC Infrared Controlled weld station.

This work is a portion of the NASA comprehensive welding program to assess industry-wide weld methods and prepare a data base for a multi-year weld development program that will provide solar array cell interconnection methodology to support the Space Station.

An initial group of 5 welded modules containing Phase II developmental 5.9 x 5.9 cm cells were subjected to cyclical temperatures of $\pm 80^{\circ}\text{C}$ at a rate of 120 cycles per day. Anomalies were noted in the adhesion of the cell contact metallization; therefore, 5 additional modules were fabricated and tested using available Phase I cells with demonstrated contact integrity. Cycling of the later module type through 12,000 cycles indicated the viability of this type of lightweight flexible array concept.

This project demonstrated acceptable use of an alternate interconnect copper in combination with large area wraparound cells and emphasized the necessity to implement weld pull as opposed to solder pull procedures at the cell vendors for cells that will be interconnected by welding. It was also demonstrated that convective (non-vacuum) temperature cycling chambers should contain positive pressure purging to minimize atmospheric inducement of stress corrosion on module interconnects in that no stress corrosion was evident in related vacuum-radiative testing through 30,235 cycles. Finally, specific recommendations were developed on related technology studies supportive to the major objectives of the NASA Welding Program.

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Section 1

INTRODUCTION

The mutually agreed objective for the LMSC weld investigation for this project was to evaluate adaptations of the welded wraparound designs which had been successfully cycled over 30,000 cycles thereby extending the technical data base and avoiding duplication. The success of the earlier design was attributable primarily to the use of Dielectric Wraparound (DWA) solar cells instead of the Junction Wraparound (JWA) cells and the use of a dynamic feedback Infrared Weld Control station which senses the cell temperature at the interconnect location as the weld is made and which terminates weld energy when a preset temperature is reached.⁽¹⁾ This earlier design also incorporated the use of a single type of one ounce copper designated Olin 110. The large area 5.9 cm x 5.9 cm DWA cells used, designated Phase I, were known to be non-optimum electrically because of series resistance associated with significant "P" contact area give away to accommodate the wrapped "N" contact.

At the beginning of the project two related options appeared promising. LeRC-JSC, for the Payload Extension Package (PEP) array concept, and LMSC, for general Independent Development, had been investigating large area Phase II cells with smaller "N" contacts and higher efficiency, 13.5% vs 12.8%. LMSC had also recently established a technical interface with the Hussey-Copper Range Company that had a copper alloy product designated Super Silver Copper or SSC-155 with higher published mechanical properties than the Olin 110. The SSC-155 was not then available in the one ounce form but Hussey located an independent rolling mill which could roll their product down to the required one ounce (1.36 mil) thickness required.

Accordingly, a test module design was proposed and accepted which incorporated the evaluation of Phase II cells and SSC-155 copper for the PC interconnects.

(1) Advances in Solar Cell Welding Technology, Larry G. Chidester and Dan R. Lott, Sixteenth IEEE Photovoltaic Specialists Conference, pp 51-56.

Section 2

TECHNICAL DISCUSSION

This report section summarizes the design of the LMSC test modules, methods of fabrication used, test facilities and test results. A background discussion is presented initially to provide a better understanding of how this project relates to the ongoing lightweight solar array development at Lockheed.

2.1 BACKGROUND

Two distinctive design features are associated with the LMSC lightweight solar array (Figure 1). These are, as listed in their sequence of development initiation, a printed circuit (PC) substrate and a wraparound electrode solar cell. Work on PC substrates was started in 1962 as an investigation to incorporate the cell interconnects into the film that served as the dielectric insulation for then-used array panel aluminum honeycomb substrates. The first PC substrate was configured for use with conventional top-bottom contacted 2 x 2 cm solar cells with the series tabs formed up out of the kapton substrate. An example of this design is shown in Figure 2. The modification in the PC design as it evolved to the configuration used for this project is summarized in Table 1. Major advantages of the PC method are that from time of fabrication it keeps the interconnects in registration for end use positioning, it provides an integral carrier-protector as opposed to individual damage susceptible separate interconnects, and it is compatible for cost effective fabrication.

The wraparound electrode solar cell, with all electrical contacts on the back (inactive) side of the cell allows single surface assembly and welding which is especially amenable for use with the PC type of circuit. Advantages are realized with no exposed interconnects or cell contacts for radiation-weapon hardened solar arrays. Most recently this cell type in a gridded back contact mode appears very promising for "transparent"-low operating temperature solar arrays. Development of the wraparound cell has been a cooperative effort between NASA and LMSC since 1972 as summarized in Table 2. The LMSC Phase I Dielectric Wraparound cell in

2 cm x 4 cm and 5.9 cm x 5.9 cm configurations comprise panel number 3, the only full size electrically active panel of the SAFE I solar array as shown in Figure 3. The 5.9 cm x 5.9 cm DWA cell type is the baseline cell for MILSTAR.

Appendix A of this report summarizes related recent LMSC IR&D welding and temperature cycling activities on DWA cells and PC substrates.

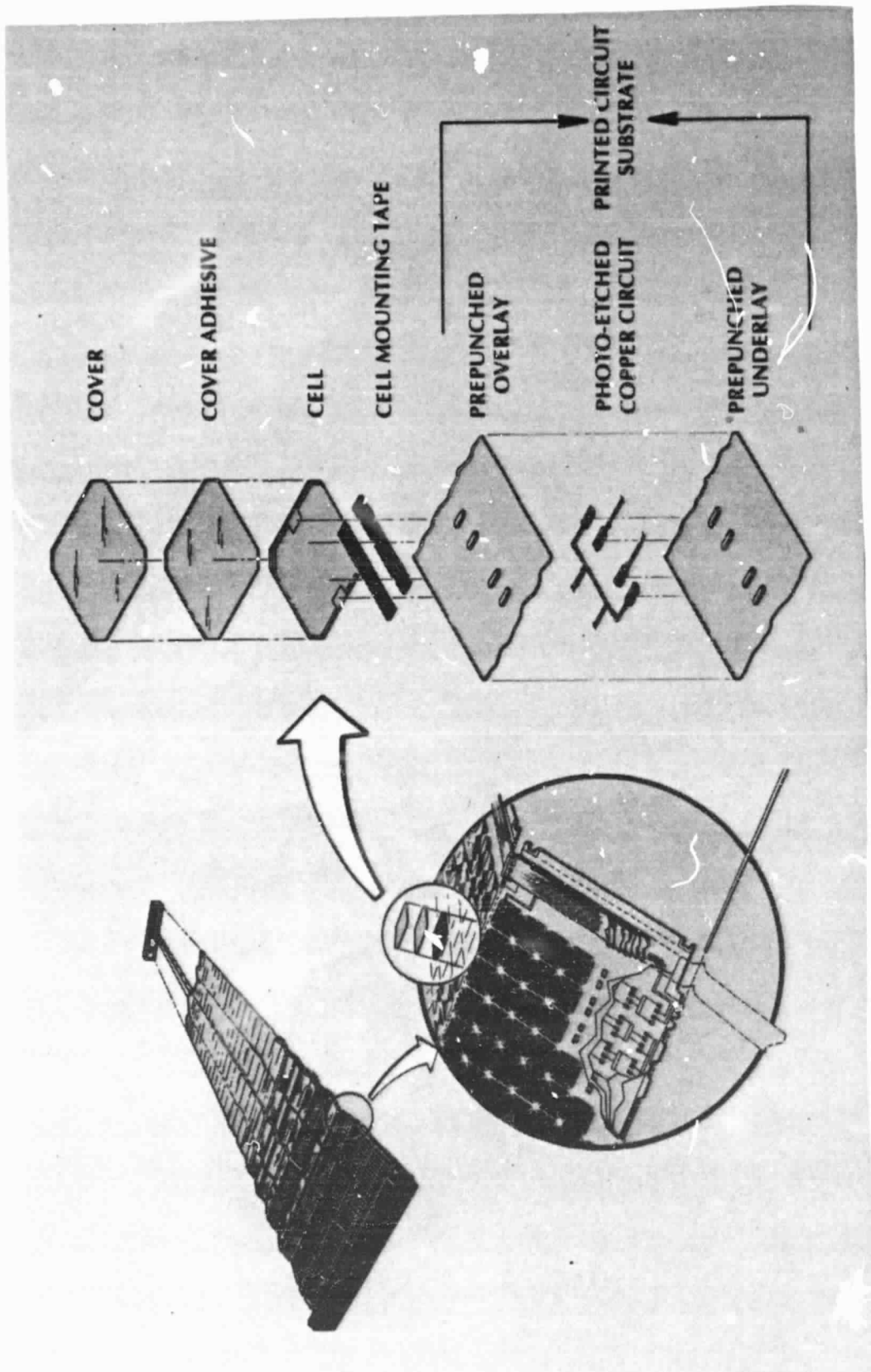


Figure 1 Exploded View of Array and Cell Substrate

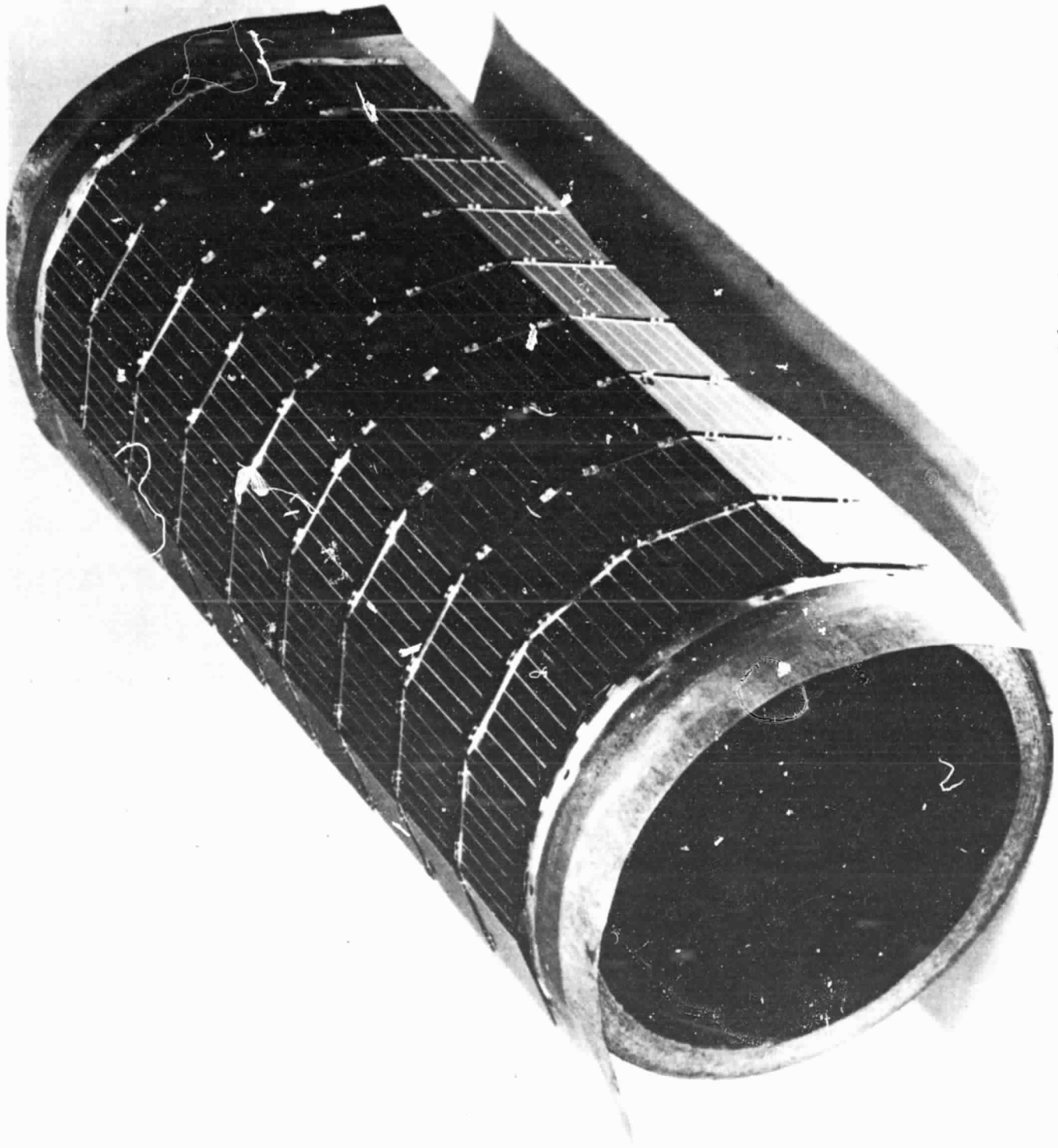


Figure 2 Original PC Copper Interconnect Substrate
with 2 x 2 cm Conventional Cells

TABLE 1
EVOLUTION OF THE LMSC LIGHTWEIGHT ARRAY PRINTED CIRCUIT SUBSTRATE

| DESIGN FEATURES | COMMENTS |
|---|---|
| <ul style="list-style-type: none"> • Copper printed circuit with kapton underlay 1 mil thick and 1/2 mil FEP adhesive layer | <ul style="list-style-type: none"> • Original concept to integrate cell interconnect with array panel dielectric used with conventional solar cells <ul style="list-style-type: none"> - Difficult to form series tabs |
| <ul style="list-style-type: none"> • Circuit modified for use with wraparound solar cells. Overlay added with solder access holes in overlay and underlay. Extensive tensile and creep/temperature tests conducted | <ul style="list-style-type: none"> • Up to 7 ea. 2 x 4 wraparound cells induction soldered simultaneously <ul style="list-style-type: none"> - Problem noted with FEP flow out in access holes and hole forming method |
| <ul style="list-style-type: none"> • Investigation of alternate adhesive layers - hole pre-punching and laser skiving evaluated | <ul style="list-style-type: none"> • Polyester found superior to FEP or epoxy - Acceptable alternate hole forming |
| <ul style="list-style-type: none"> • Investigation of welding as interconnect method in lieu of soldering | <ul style="list-style-type: none"> • Feasible for weld assembly <ul style="list-style-type: none"> - Interest in increasing pull strength |
| <ul style="list-style-type: none"> • Rolled annealed (RA) copper used instead of Electro Deposited (ED) copper | <ul style="list-style-type: none"> • Significant increase in pull strength and temperature cycle life <ul style="list-style-type: none"> - Rapid oxidation of copper surface required many cleaning steps |
| <ul style="list-style-type: none"> • Oxidation inhibitors evaluated | <ul style="list-style-type: none"> • Process incorporated which properly protected exposed interconnect |

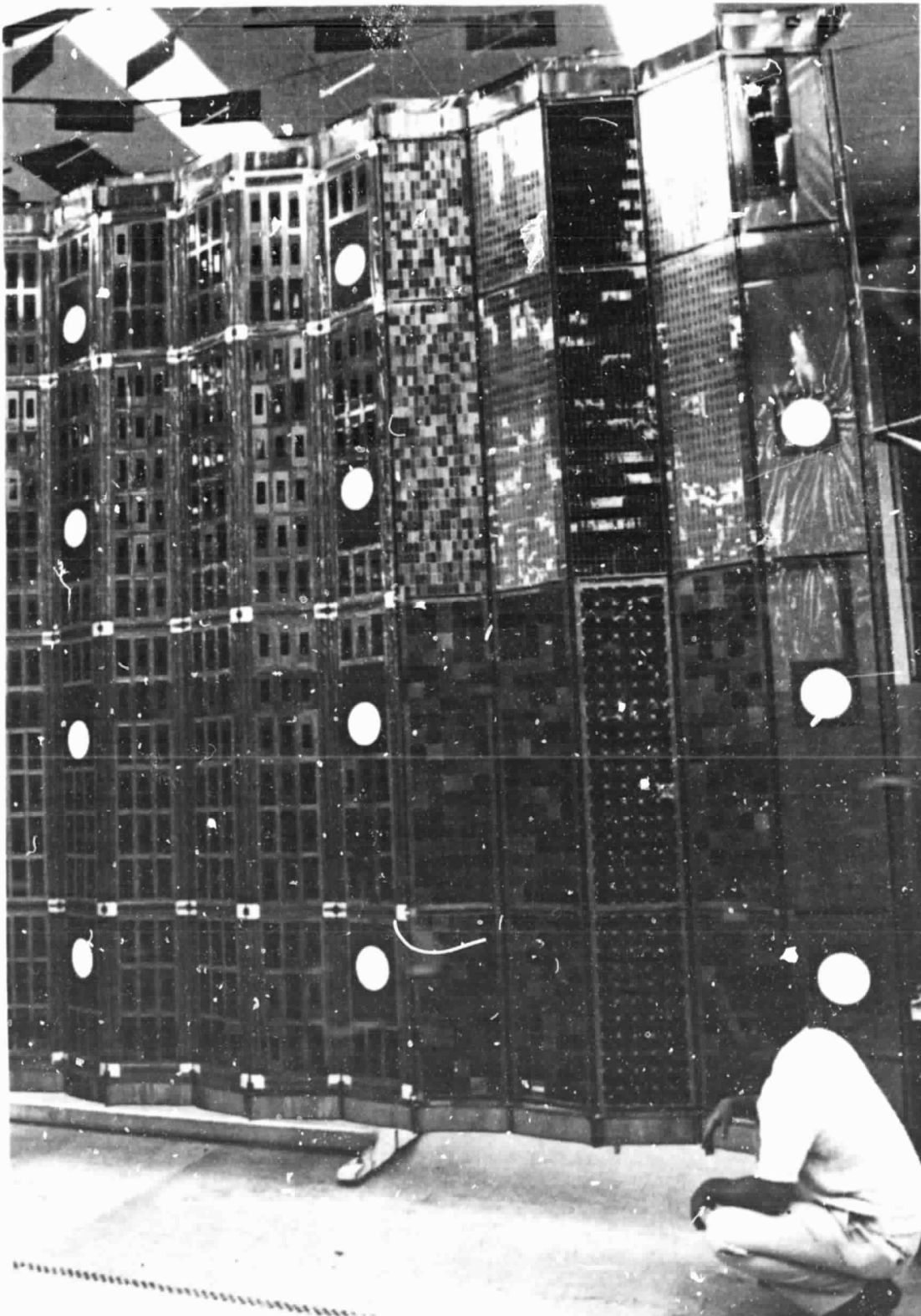


Figure 3 SAFE I Active Solar Panel

TABLE 2
LMSC FLEXIBLE SOLAR ARRAY TECHNOLOGY NASA CONTRACTS

| TITLE | AGENCY | PERIOD OF PERFORMANCE | WRAPAROUND CELL RELATIONSHIP |
|---|-----------|------------------------|---|
| Space Station Solar Array | NASA-JSC | 1969 - 1972 | Original 2 x 4 "T-Bar" design |
| SSSA Technology Evaluation NAS9-11039 | NASA-JSC | 1972 - 1973 | Original 2 x 4 "T-Bar" design |
| SA Flex Design Optimization NAS8-28432 | NASA-MSFC | 1973 | Efficiency improvement-end tab options. First weld investigation. |
| Study of Multi-kW Solar Arrays for Earth Orbit Application NAS8-32981 | NASA-MSFC | Mar 1979 - Jun 1984 | Superstrate incorporation of large area JWA cells |
| Low Cost Solar Array (add on to above) NAS8-32981 | NASA-MSFC | Aug 1980 - Jul 1981 | Superstrate incorporation of large area JWA cells |
| Modules for Plasma Study NAS8-34026 | NASA-MSFC | Aug 1980 - Jan 1981 | Used welded 5.9 x 5.9 DWA cells |
| SEP Solar Array Development & Shuttle Flight Experiment NAS8-31352 | NASA-MSFC | Sep 1975 - Mar 1981 | IR weld control of panels with 2 x 4 and 5.9 x 5.9 cells |
| Solar Array Flight Experiment | NASA-MSFC | 1981 - 1984 | First orbital test of wraparound solar cells |
| 25 kW Power Module | NASA-MSFC | Mar 1978 - Nov 1978 | Array concept study based on DWA cell technology |
| Assessment of SEP Solar Array Technology for OSM Application | NASA-JSC | May 1979 - Sep 1979 | Adaptation of wraparound cell arrays to OSM |

TABLE 2 (cont.)
LMSC FLEXIBLE SOLAR ARRAY TECHNOLOGY NASA CONTRACTS

| TITLE | AGENCY | PERIOD OF PERFORMANCE | WRAP AROUND CELL RELATIONSHIP |
|--|--------------------|------------------------|---|
| Concentrator Enhanced SA JPL 955110 | NASA-JPL | Jun 1978 - Oct 1978 | Concentrator array concept study based on DWA cell technology |
| SEP SA Modifications (Ultra-Low Mass Blanket) JPL 955070 | NASA-JPL | May 1978 - Jul 1978 | Assessment of thin solar cells |
| Lightweight Blanket 956020 | NASA-JPL | 1981 - 1983 | Welded interconnection of thin (2 mil) silicon cells |
| SA Weld 956020 - this report | NASA-JPL (LeRC) | 1983 - 1984 | (Per this report) |
| Demonstration of Transparent Solar Array Modules 956608 | NASA-JPL | 1983 - | Evaluation of low temperature large area gridded DWA cells |

2.2 DESIGN

In accordance with the contract statement of work, a module design was developed which incorporated 9 cells attached to a PC substrate that is tensioned with springs in a perimeter frame to simulate deployed array tension. The tension selected duplicates that of the SAFE I solar array, 20.6 grams per centimeter.

GENERAL CONFIGURATION

Solar Cells

All solar cells for test coupons and modules were designated to be of the Dielectric Wraparound (DWA) type and they were also restricted to large area cells $> 25 \text{ cm}^2$. In order to properly simulate thickness, mass and heat sinking characteristics for welding, filtered cells (cell assemblies) were designated to be used exclusively. Cells were the single crystal (CZ) type nominally 200 microns thick. Cells were to be processed using low rate plating or subsequently annealed to minimize hydrogen atom entrapment in the plated silver. It had earlier been determined that hydrogen atoms could be contributory to stress corrosion of welded interconnects.

Cell Covers

0211 microsheet nominally 150 microns thick was selected. All covers were to be AR coated with UV multilayer interference filters optional.

Filtering Adhesive

The cover assembly or filtering adhesive selected was DC93-500.

Interconnect Metal

One ounce rolled copper (≈ 36 microns thick) was the baseline interconnect metal. Olin Brass Sommers Division and Hussey/Copper Range were the acceptable vendors. Electro Deposited (ED) copper was not allowed because in earlier tests it was shown to have poor pull strength. Acceptable candidate copper compositions were then as follows:

- Hussey/Copper Range Super Silver Copper SSC-155
- Olin 110
- Olin 194
- Olin LTA
- Other copper foils which are available in one ounce foil and which have comparable electrical (IACS) and mechanical properties to those listed above

Interconnect Design Geometry

Previous testing, including 7 year LEO, had demonstrated that, with DWA cells and Cu interconnects in a kapton-polyester laminate, in-plane stress relief, i.e., serpentine patterns, do not enhance cycle life. Therefore, simple straight line designs with appropriate cross-sectional area and redundant traces were utilized.

Module Substrate

The module substrate selected was an underlay-overlay of 25 micron kapton-13 micron polyester which are prepunched to provide circuit windows at designated positions. Circuit etching and substrate preparation were in accordance with established LMSC processes. The kapton "machine direction" was co-linear with the cell series direction. The PC substrate was so configured that after processing cell series and parallel spacing was no less than 600 microns.

Module Mounting and Tensioning

Each module was mounted in a separate perimeter mounting frame as depicted in Figure 4. The module was clamped along its bottom frame edge parallel to the series direction and the opposite edge was mounted in a clamping bar which is attached to the perimeter frame top rail by tension springs which apply 20.6 grams/cm (ref. SAFE I 18.2 lb array tension deployed on 13.17 ft width).

General Nomenclature and Use--Cells, Coupons, Modules

In compliance with the deliverable hardware requirements of contract 956020 Supplemental Agreement Modification No. 4, the planned types, quantities, and

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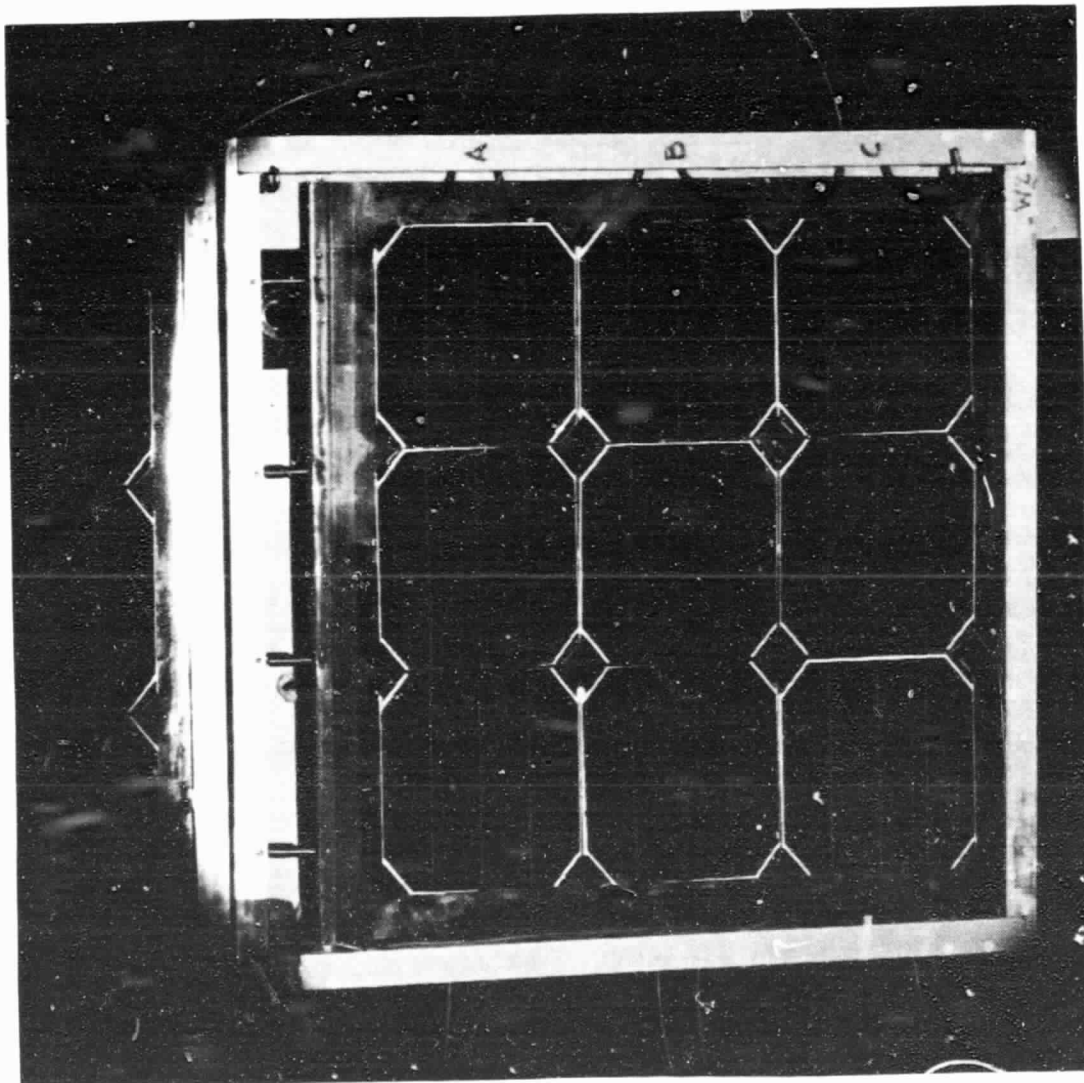


Figure 4 Test Module in Mounting Frame

use of modules are shown in Figure 5. As noted, eight modules were to be built, five welded and three soldered. Three welded units, W-1, W-2, and W-3, along with two soldered units, S-1 and S-2, were shipped to NASA. Unit W-1 was returned to LMSC for temperature cycling in combination with W-4, W-5, and S-3. More than eighteen coupons were provided to NASA for their own test and evaluation. Figure 6 shows the large area DWA cell types which were under development or available from the cell vendors at the initiation of contract work. It indicates the Phase II centerline and Phase II 2 tab cells that were used for the initial test modules and later the Phase I cells used for the restart modules.

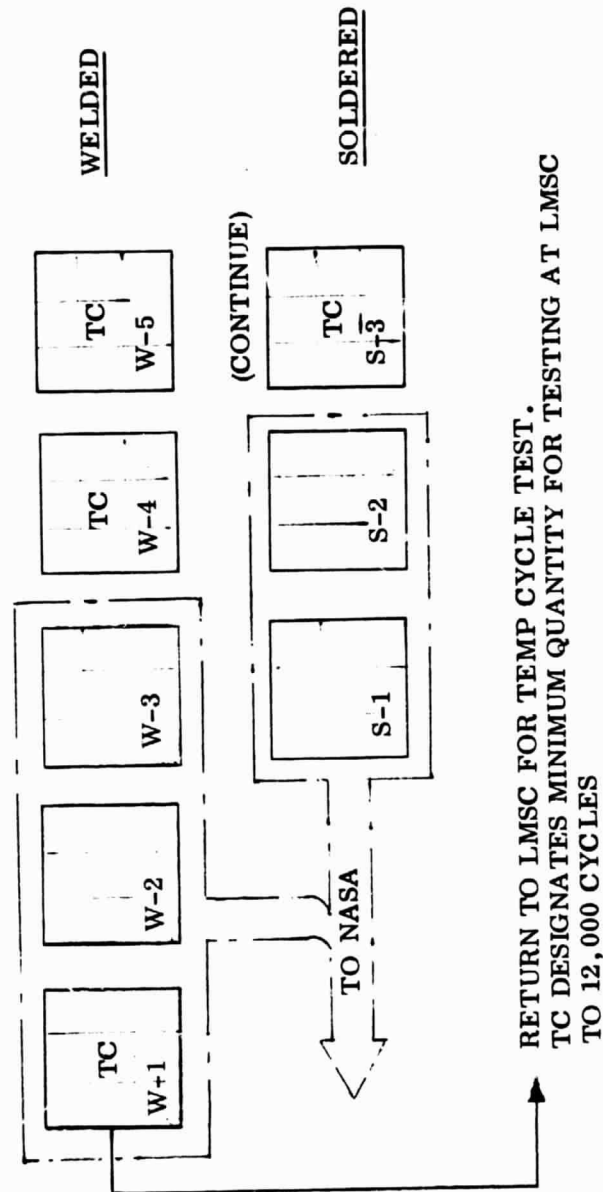


Figure 5 Contractually Required Modules

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Phase I 5.9 x 5.9

Phase II 2 Tab

Phase II 6

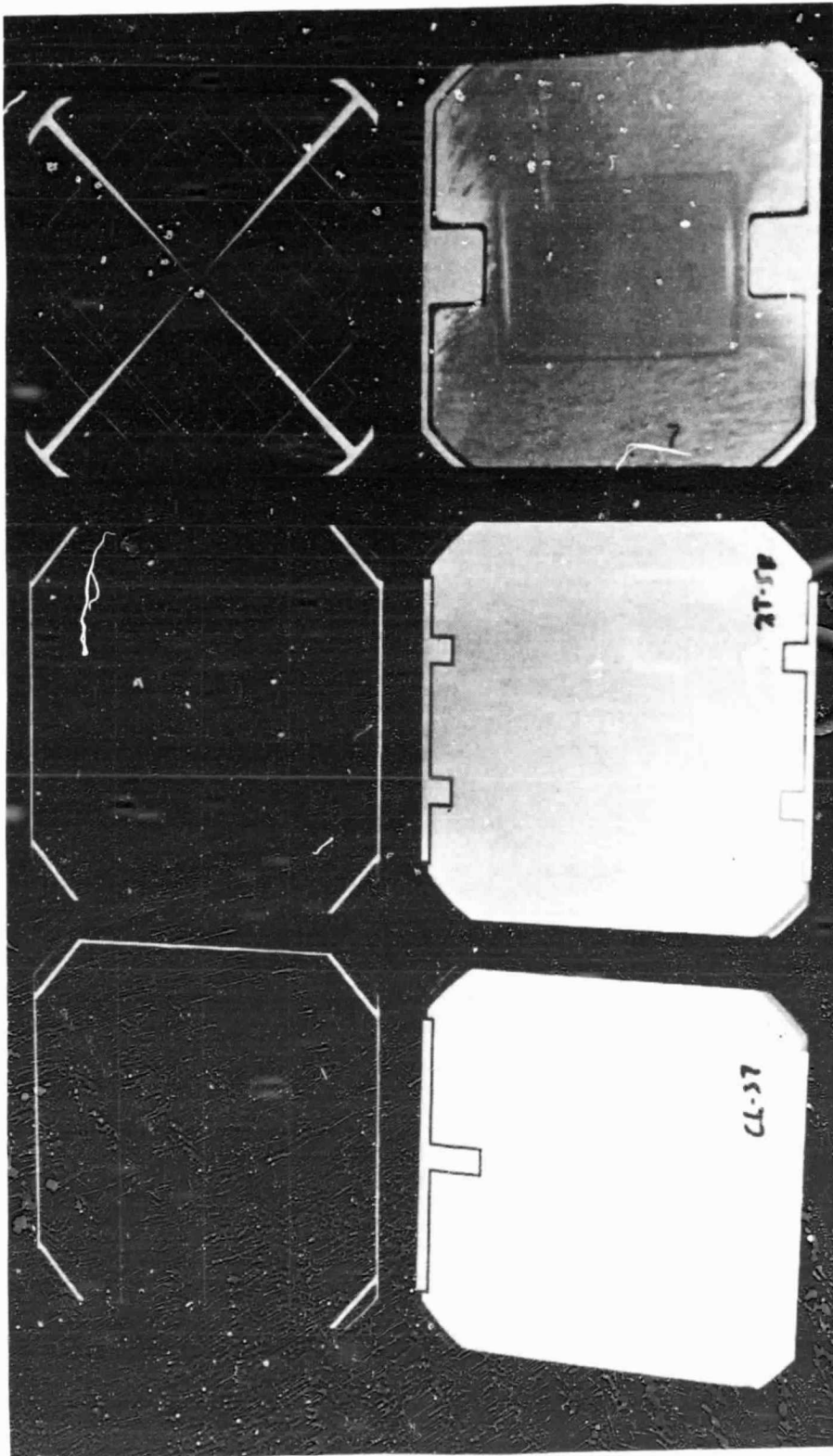


Figure 6 Available Large Area DWA Cells

2.3 FABRICATION

The emphasis in the fabrication phase was on weld schedule selection and technical assessment of one ounce copper materials for interconnects. The printed circuit substrates can be laminated to adhere the copper to the underlay (1 mil of kapton and 1/2 mil of polyester) and to lock in the photo defined-chemically etched circuit with an overlay (reverse of the underlay) by any one of three different methods.

These are: a) roll lamination, b) platen or press lamination or c) elevated temperature vacuum bagging similar to an autoclave technique. LMSC has used all of these methods for fabrication of flexible substrate solar array circuits. The method selection is dominantly dependent on the size of the circuits and the total quantity required. The oven-vacuum bag technique, the method used on this program, is the most cost effective for small test specimens.

The perimeter frames, reference Figure 4, were built using available aluminum extrusions for both the end bars and the side bars. The module circuit is locked into the lower attachment bar by folding the bottom of the circuit laminate and taping it with kapton-silicone adhesive tape to form a loop--slipping the loop into the mouth of the extrusion--then inserting two .060 diameter fiberglass pultrusions. The top of the module is folded over a .040 x .20 x 8.0 in drilled header bar, adhered on both faces with 3M Isotac pressure sensitive acrylic tape, topped with kapton-silicone tape and attached to the perimeter frame top extrusion with tension springs.

Weld Schedule Certification

All welding for this project used the LMSC Weld Station with IR Dynamic Control. Optimum weld schedules were developed by comparing pull strength, joint visual appearance, joint infrared microscope, normal and polarized signatures, and joint microsections with existing LMSC weld joint data.

Pulls

For a selected weld schedule optimization run, which followed general broadband schedule investigations, 5 pulls were made, both parallel to the weld tip axis

(major tip axis) and transverse to the weld tip axis for a designated weld system IR setting. No less than 3 sets of pulls corresponding to a "minus tolerance," "nominal," and "plus tolerance" IR setting were run to characterize each cell candidate P contact-N contact case.

Angle of Pull

All pulls were made at 45° using the following equipment:

- Puller
Unitek Micropull Model 6-092-03, Serial No. 44994
- Gauge
Hunter L-500M (grams)
Chatillon DPP-5 kg (grams)
Chatillon DPP-80 (pounds)

Pull Tabs

The baseline interconnect material used by LMSC in lightweight, flexible arrays is Rolled Annealed (RA) 1 oz. copper. Accordingly, discretely-formed copper pull tabs that are photo-etched were used. Several thin strip copper alloys were investigated including Olin 110 as rolled (AR) Olin 110 rolled annealed (RA), Olin 194, as rolled (AR), SSC 155 annealed and SSC 155 tempered. With identical pull tabs, cell blanks and weld schedule the average of 5 pulls for each material was:
Olin 110RA - 1.77 lb, Olin 110AR - 1.56 lb, Olin 194 AR - 1.77 lb, SSC 155RA - 2.51 lb, and SSC 155 tempered - 2.98 lb.

All the materials investigated were compatible with parallel gap welding and in particular with the LMSC weld station using infrared signal feedback for weld termination. The prior successful long life temperature cycling had been with test modules fabricated with annealed copper; therefore, even though the SSC 155 tempered exhibited the highest pull test values, it was not selected for the actual test modules for this contract.

Additional investigations were conducted in the fabrication phase to further characterize the comparative mechanical properties of the two primary interconnect material candidates, Olin 110 and SSC 155. Ductility is an important parameter in total cycle life; therefore, Mullen Bulge tests were run on representative segments of the copper foil wherein a hemispherical arbor is forced into the clamped copper segment. Bulge height at burst and burst pressure (psi) are recorded. From this data elongation was derived as follows: SSC 155AR - 10%, SSC 155RA - 32%, Olin 110AR - 0.5%, and Olin 110RA - 10%.

The data was consistent for specimens received from Hussey/Copper Range, the SSC 155 supplier, for two different sample lots.

MODULE FABRICATION

Each module contained a total of 9 DWA cell assemblies configured such that 3 each strings of 3 cells in series were contained therein. Each string contained accessible positive and negative terminals such that by the use of external jumpers, different series/parallel options could be configured.

Module Fabrication Setup

After mounting tape has been applied to each cell, the nine cells for each module were inverted in the LMSC 5.9 x 5.9 cell vacuum chuck to maintain proper series and parallel spacing. Then vacuum was applied, the tape carrier paper removed and the PC module substrate overlayed on the positioned cells. Next, the mounted cell assemblies and their substrate were positioned for welding at the LMSC Weld Station.

Electrical Measurements

Prior to assignment to modules, each cell was tested electrically. Modules were tested after interconnection in the 3 each 1 x 3 configuration. The electrical measurements were made in the LMSC Electrical Power Systems laboratory using an X-25 Mark II Spectrosun light source, the #167 secondary standard, and a HP 3052A Automatic Data Acquisition System.

Module Inspection

All modules were inspected at 10X or higher magnification. Any anomaly or defect which could adversely affect cycle life was cause for rejection and rework. Minor factors such as small cell/cover chips or edge cracks which have no effect on cell electrical performance initially or through the projected 12,000 cycles were not cause for rejection. Historical "cosmetic" aberrations were not cause for rejections.

Instrumentation - Thermal

After the modules are completed and mounted in their perimeter tensioning frames three copper-constantan thermocouples were installed on the middle cell of each module. No. 1 TC was on the top of the cell over a collector bar to minimize shadowing losses, No. 2 TC was on the back of the cell, and No. 3 was on an exposed copper trace adjacent to a "P" contact weld joint of the middle cell. Two mil TC wire was used to minimize wire thermal conduction heat sinking anomalies and the TC wires were tied to the frame such that mechanical loads could not be transmitted to the modules or cells.

2.4 TEST

The cyclical testing $\pm 80^{\circ}\text{C}$ at a nominal rate of 120 cycles per day was done in the LMSC Electrical Power Systems Quick-Look I chamber. This same chamber was used for the 41,093 cycle test discussed in the appendix. The chamber will accommodate 6 modules (reference Figure 7) in the horizontal position. Figure 8 is an overall view of the chamber and control console. Figure 9, viewed through the chamber window, shows the modules under test. The chamber consists of a closed-vented aluminum liquid nitrogen plenum in the bottom, a quartz heat lamp bank overhead and a moveable horizontal tray, where the test specimens are placed. The tray sequentially moves from near the plenum to up underneath the heat bank through a displacement of 4.5 inches. Power to the heat bank is continuously controlled to follow the heat-up/cool-down slope memory in the electronic controller. Figure 10 is a segment of the actual module temperature profile from the system recorder.

Listed below are the P/Po results of out of acceptable tolerance circuits on three of the welded modules. After 5163 cycles testing was terminated on these units.

| Circuit | 500 Cycles | 5163 Cycles |
|---------|------------|-------------|
| W1A | 88.7% | 77.0% |
| W1C | -- | 89.2% |
| W4A | 87.6% | 85.5% |
| W4C | -- | 80.9% |
| W5B | -- | 87.0% |

The high degradation tendency was noted on the A circuits of modules W1 and W4 at 500 cycles. Examination of the degraded modules revealed that joint separation had occurred due to the cell "N" contact metalization lifting off some of the cells in the designated circuits. In no case was the contact lift-up in the weld at the interface between the copper interconnect and the top surface of the cell contact metalization. Further, evaluation reconfirmed that the lift-up was not due to an overweld condition; all weld station parameters had been according to specified weld schedules.

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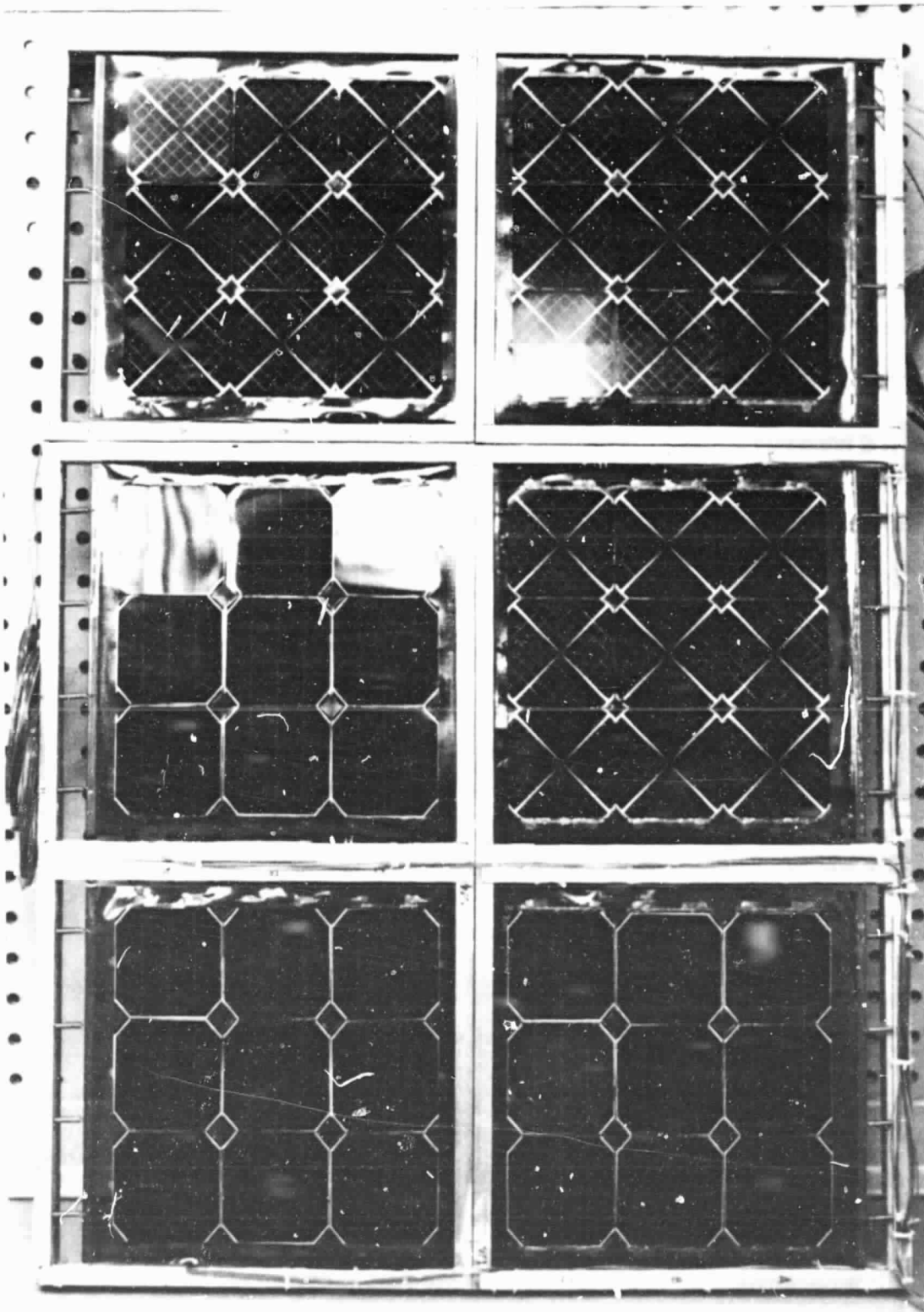


Figure 7 Six Module Test Frame

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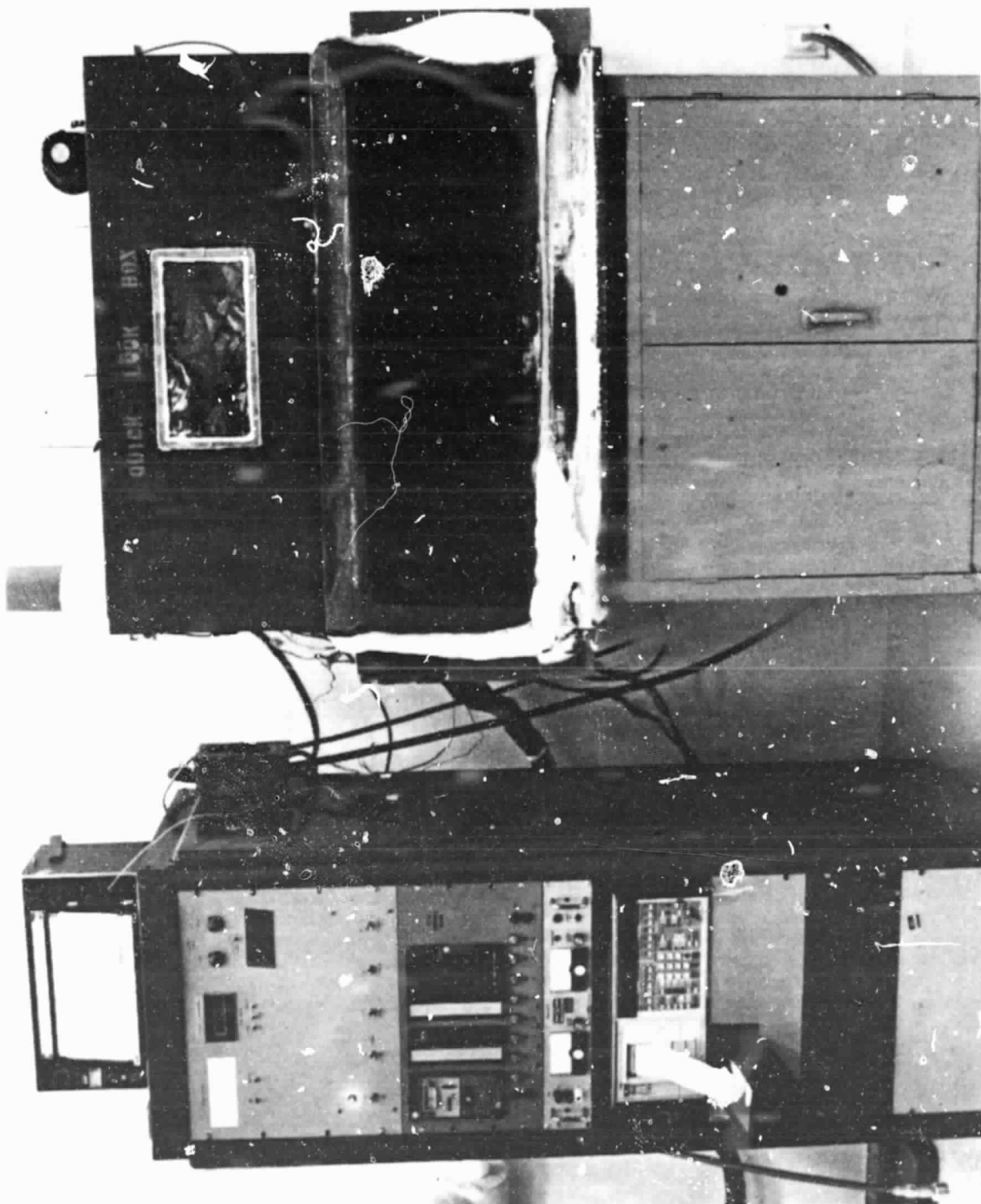


Figure 8 Quick Look Thermal Cycling Chamber

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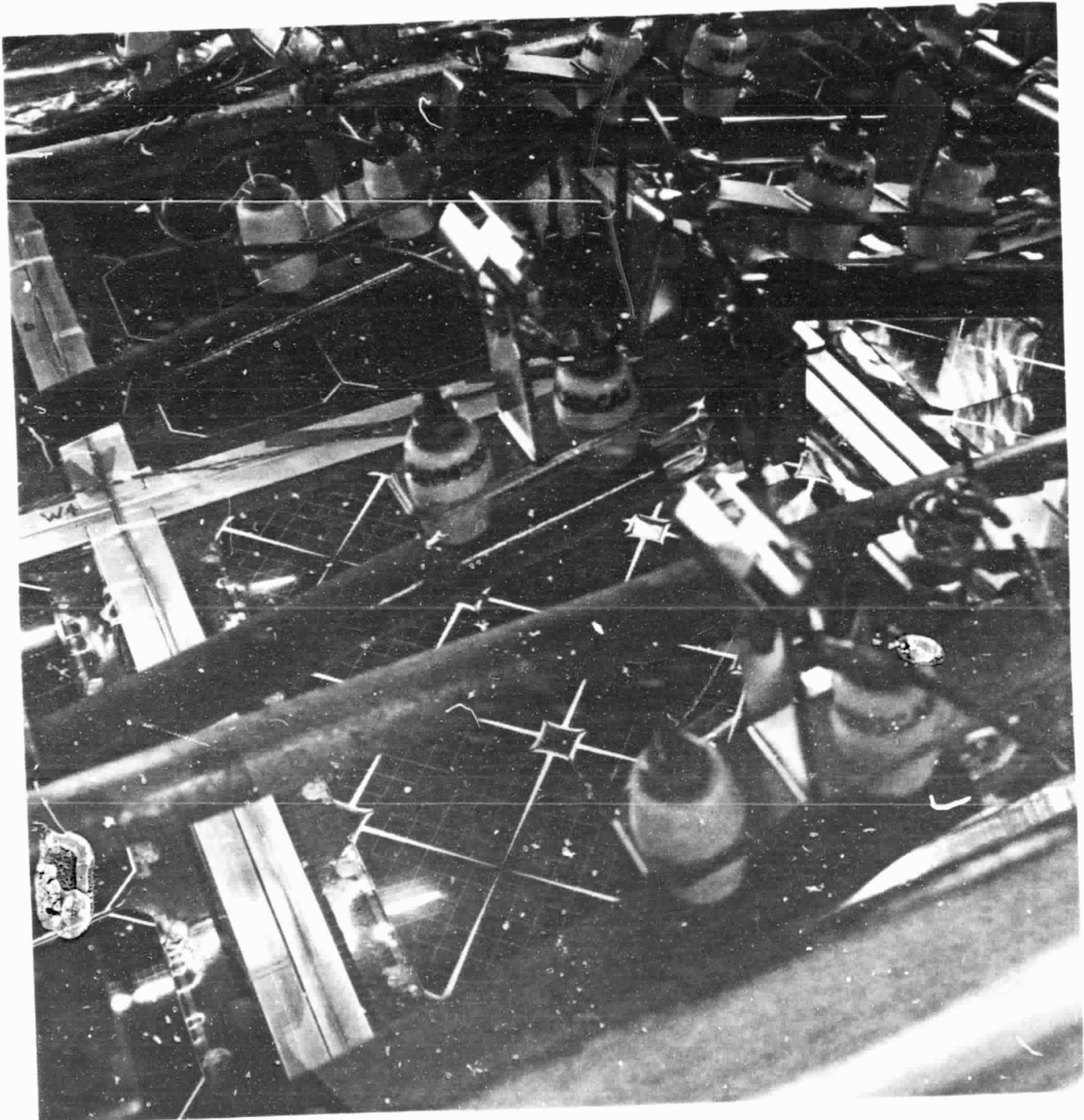


Figure 9 Modules Under Test

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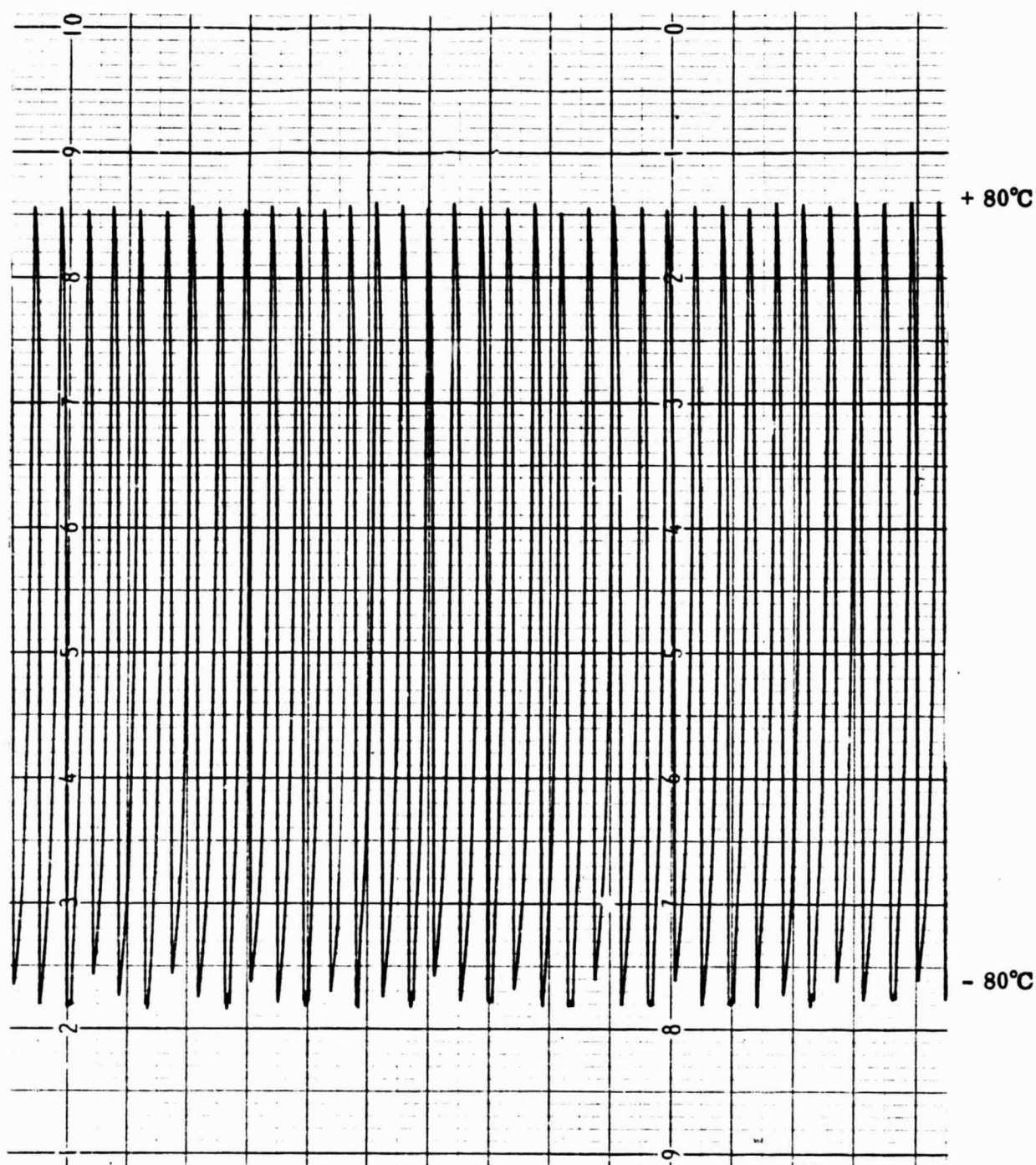


Figure 10 Typical Temperature Profile

An extensive investigation was initiated to identify the factors which could be contributing to the contact weakness on the Phase II cells. Using the selected weld schedule a series of weld-pull strength evaluations were conducted on ASEC Phase II cells from run no. 1, where there was a high level of engineering assistance and surveillance in fabrication of the cells, run no. 2 which was the 2800 cell PEP program run where AQL level contact pull tests were imposed, from ASEC Phase I where 100% contact pull test were imposed, and from some early Spectrolab 5.9 x 5.9 cm DWA cells which were received after the initial set of modules had been built and were under test. The results of this evaluation are given below.

"N" CONTACT PULL DATA

| <u>Cell Type</u> | <u>Percent of Cell Metallization Failures</u> | <u>Avg. Pull Strength (lb)</u> | <u>Pull Range (lb)</u> |
|----------------------|---|--------------------------------|------------------------|
| ASEC ϕ II Run 1 | 62.5 | .96 | .4 - 1.5 |
| Run 2 | 81.0 | .81 | .15 - 1.5 |
| ϕ I | -- | 1.22 | .9 - 1.5 |
| SPL | 18.8 | 1.29 | 1.0 - 2.0 |

In the case of the Spectrolab cells the 3 contact metallization failures which occurred were higher than 1 lb. All of the pulls for ASEC Phase I and SPL were failures of the pull tab; therefore, actual joint strength is higher than that noted.

The cycle results and the comparative pull data indicated that cell processing anomalies could be contributory to the weaker contact strength on Phase II cells; therefore, a high priority task was conducted to assess contact weld pull strength use vs cell process variables. The three primary variables considered to be most likely contributing to the cell contact adhesion weakness were the apparatus used for applying the CVD dielectric layer under the "N" contacts: a) the turntable reactor used for the Phase II cells as opposed to the multipass belt reactor used for the Phase I cells, b) the vacuum evaporator chamber used for all contact application, or c) the presence of

the Back Surface Reflector (BSR) aluminum layer. The summary findings were:

- Joint pull values were 2.8X stronger for the samples fabricated in the old evaporator and were higher by an average of 1 lb. The new chamber had been used for the majority of the Phase II cells.
- There was no discernible change with or without the BSR layer and whether or not the layer was thick or thin.
- The newer CVD turntable CVD reactor improved joint strength.
- Reduced energy weld schedules did not improve Phase II cell contact strength.
- None of the consistently high contact strength Phase II cells were processed in the new chamber.

Therefore, with the new chamber isolated as the dominant variable, subsequent investigation with contaminant monitors in the chamber revealed a malfunctioning valve and low-level outgassing from support bracketry which was not stainless steel. This introduced deleterious oxides at the dielectric-BSR aluminum interface.

To avoid the expenditure of time and funds for chamber recertification and fabrication of more Phase II cells it was decided to build restart modules using available Phase I cells for units W6, W9, and W10 (which was shipped to NASA LeRC), recently available SPL DWA 2 ohm BSR cells for W7 and SPL 10 ohm BSF gridded cells for unit W8. The results of testing of the restart modules through 12,000 cycles is given in Table 3. The 12,000 cycle data is the average of three separate electrical IV runs on the circuits. The drift down in output is due to higher circuit series resistance due to microcracking around some of the weld joints attributable to stress corrosion caused by insufficient positive nitrogen purge pressure in the chamber used. Consequently, plant gaseous nitrogen plus a pressure valve are being added to the chamber to assure elimination of ambient oxygen/humidity.

TABLE 3
RESEART MODULE OUTPUT CHANGE VS CYCLES (P/Po)

| 5.9 x 5.9 Cell Type | Module | 500 Cycles | | 6060 Cycles | | 12,000 Cycles* | |
|------------------------|--------|----------------------|-------|----------------------|------|----------------------|------|
| | | Circuit Module Group | | Circuit Module Group | | Circuit Module Group | |
| ASEC Phase I | W6-A | 100.2 | | 95.8 | | 56.6 | |
| | B | 98.8 | 98.8 | 96.2 | 96.9 | 95.1 | 95.3 |
| | C | 97.5 | | 98.7 | | 94.3 | |
| SPL | W7-A | 103.7 | | 98.5 | | 95.3 | |
| | B | 99.6 | 101.2 | 98.2 | 98.1 | 96.0 | 95.6 |
| | C | 100.3 | | 97.5 | | 95.6 | |
| 2 Ohm BSR | | | | | | | |
| | | | | 100.4 | 97.9 | | 96.3 |
| | | | | | | | |
| SPL | W8-A | 103.1 | | 99.1 | | 99.1 | 98.1 |
| | B | 101.3 | 101.2 | 97.5 | 98.6 | 95.6 | |
| | C | 99.3 | | 99.1 | | 99.6 | |
| 10 Ohm BSF Gridded | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| ASEC Phase I | W9-A | 103.0 | | 98.3 | | 97.4 | |
| | B | 98.7 | 100.3 | 97.0 | 97.8 | 94.2 | 96.3 |
| | C | 99.3 | | 98.1 | | 97.4 | |

*average of 3 IV runs

3.0 CONCLUSIONS

- Accelerated temperature cycle testing is a valuable technique for assessing:
 - the strength of the metallurgical bond of the contacts on the cell to the silicon, to the metal layers in the "P" contact and to the constituent dielectric layers of the wrapped "N" contact in a DWA cell
 - the cyclic survivability of the weld joint
 - life limiting factors of the array design tested
- Solar cell process/procedures and fabrication equipment certification and repeatability are of paramount importance for welded interconnection and subsequent temperature cycling survivability
- For the solar cells evaluated, the most cost effective method of plating approximately 4 microns of silver over the vacuum evaporated flash layer did not impact contact strength and cycle life
- Incorporating an aluminum layer as a Back Surface Layer (BSR) on the cell did not lower contact pull strength
- SSC-155 one ounce copper is now certified as an acceptable substitute for Olin 110. It can be obtained in 24" roll widths similar to the Olin 110.
- Paste aluminum processed BSF cells, previously considered impossible or difficult to weld, were incorporated in a welded module and cycled successfully through 12,000 LEO cycles. Surface smoothness constraints on cells for welding should be reduced and re-evaluated.
- Under this project for the first time, large area DWA gridded back contact cells were successfully cycled through 12,000 LEO cycles.

4.0 RECOMMENDATIONS

Six specific recommendations are suggested as a direct result of the findings of this project.

- Accelerated convective temperature cycling chambers should be instrumented to verify positive purge pressure with inert gas.
- If the chamber does not accommodate in-situ electrical I-V tests of the specimens, the turnaround time for outside test should be minimal.
- Specimens not being cycled should be stored in purged cabinets.
- Lightweight welded array designs which use printed circuit substrates should couple the substrate to the cell assemblies with adhesive or pressure sensitive tape to provide a mechanical joint which constrains the cyclical deformation of the substrate.
- Vendor provided solar cells intended for welded interconnection should have their contact process and pull strength certified via weld pull tests, not solder pull tests.
- Vendor cell contact metallization chambers should incorporate leak and contaminant monitoring devices.

Additional general recommendations are submitted to provide the basis for future studies that would expand the utility of the NASA Welding Project.

- Unlike soldered interconnection where heat up separation of the joint can occur, welded joints are permanent in nature. Welded interconnection repairability concept studies should be initiated.
- There has been a recent emphasis in the qualification of GaAs cells for space application. It would be appropriate to initiate programs which assess welding as the assembly method for GaAs solar arrays.

- On an intermittent basis since 1973 it has been demonstrated that weld joint signatures are perceptible in an NDT mode using infrared microscopes. Further work would be beneficial in quantifying the correlation of signature to weld schedule and in assessing the incorporation of this NDT method for real time weld station joint product assurance.
- Welding work published to date has contained minimal results on the metallurgical characterization and structural modeling associated with this bonding method. Tasks should be initiated to survey and summarize these important related technologies and to initiate further associated studies.
- The work reported here (reference Appendix A) is the only known correlation of identically prepared welded test specimens in accelerated non-vacuum cycling and near real time vacuum cycling. It would be very valuable to be able to specify the cycle life time multiplier factor that associates successful accelerated cycling with orbital life projections. Testing and structural analysis which correlates accelerated-low cost test methods with real time space environment life should be initiated.

5.0 NEW TECHNOLOGY

No new technology was developed during the project or as a result of the related engineering and testing activities.

APPENDIX A

RELATED LMSC WELDING AND TEMPERATURE CYCLING ACTIVITIES

Correlating Accelerated Quick-Look Testing to Vacuum-Radiative Testing

The type of testing predominantly used to evaluate material, component or design deficiencies on new and evolving solar array concepts is accelerated temperature cycle testing. The testing must be done on an accelerated basis in order to provide data in a time frame which can give input in the design and development phases. Some experimenters have used dip-shock testing where cells and cell assemblies are immersed in liquid nitrogen (-320°F) then in boiling water ($+212^{\circ}\text{F}$). This method, though low in cost, is limited in the size of test specimens and obviously induces loads completely unrelated to orbital environments. It also may result in rejection of cell-interconnection designs which would function well in the more benign actual flight conditions. The real time-on orbit cyclical temperatures an array is subjected to introduces lower stresses than the developmental testing; therefore, real mission lifetime will exceed demonstrated accelerated or quick-look testing by some factor. This factor is not completely known but an indication is given by comparing MSFC vacuum radiative testing results with LMSC quick look results. Table A-1 identifies the differences in the two test methods.

Description of Test Panels

The 96-cell panel which was tested at LMSC, reference Figure A-1, was subjected to an initial major test program where it experienced 38,300 cycles in the same "Quick Look" chamber used for the project of this report. It was then used to calibrate a new quick-look chamber where it was subjected to 100 additional cycles. In the interval, when the restart modules were being fabricated, it was subjected to 2693 more cycles. Its total cycle history is summarized as follows:

| | |
|--------------|--|
| 38,300 | LEO Cycles $\pm 80^{\circ}\text{C}$ |
| 100 | Reference Cycles $\pm 100^{\circ}\text{C}$ |
| <u>2,693</u> | LEO Cycles $\pm 80^{\circ}\text{C}$ |
| 41,093 | Cycles TOTAL |

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TABLE A-1
LMSC AND MSFC THERMAL CYCLING SUMMARY

| Parameter | LMSC | MSFC |
|---|---|---|
| Chamber Type | Purged Dry Nitrogen | Vacuum |
| Thermal Transfer | Convective and Radiative | Radiative |
| Temperature Range | $\pm 80^{\circ}\text{C}$ ($\pm 100^{\circ}\text{C}$ for 100 Cycles) | +90 to -105°C |
| Cycle Rate | 10 to 12 min | 17 min |
| Modules Tensioned | Yes | Yes |
| Module Position | Horizontal - Cells Up | Vertical |
| Module Motion | Moves from LN^2 Plenum to Heat Banks Each Cycle | Static |
| Demonstrated Accelerated Cycle Life | 41,093 | 34,475 Cycles |
| Electrical Performance | Within Measurement Tolerances(a) | Within Measurement Tolerance |
| Module Type | 2 x 4 cm, 96-Cell | 2 x 4 cm, 256-Cell P Contact Load Paths Cut on Half of the Cells |

(a) Excluding one cell inadvertently taped down improperly

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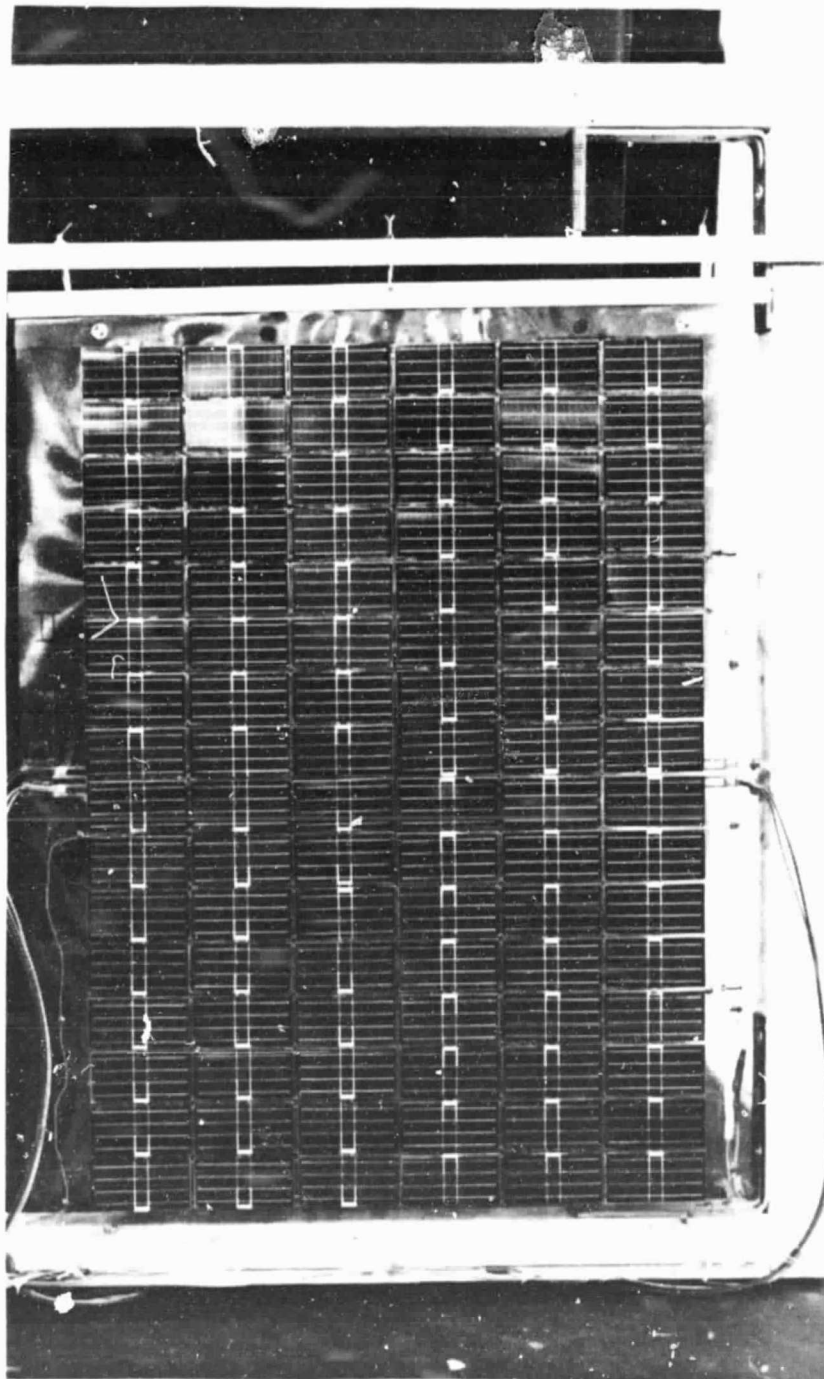


Figure A-1 96 Cell Panel

For a solar array at 300 nautical miles, earth eclipsing cycles per year would be 5475 or 31,063 cycles for 7-1/2 years. The unit therefore demonstrated design compatibility for missions equal to or greater than 7-1/2 years at the designated altitude. The only life limiting anomaly noted was where one of the circuits in the 96-cell panel degraded due to significant micro-cracking on one cell where the cell mounting tape had inadvertently been left off adjacent to the two "P" weld joints. It was also demonstrated in another specifically configured test where cell assembly to PC substrate tape or adhesive was purposely deleted that a 46% greater population of weld joint perimeter microcracking occurred than with the properly taped control circuit. Obviously with the higher cross section and modulus of the solar cell assembly, it acts like a laminated beam in the system and constrains the out of plane heat up bending and cool down contraction of the PC substrate and minimizes microcracking of the interconnect caused by interconnect deformation.

The 256 cell panel, tested at MSFC is shown in Figure A-2. It was built at the same time with the same weld station and weld schedule as the 96 cell unit.

256 Cell Panel Vacuum Radiative Testing Results

In January 1984, the subject panel was inspected joint by joint under magnification to determine if joint micro-cracking had occurred associated with vacuum-temperature cycling such as has occurred with the similar 96 cell panel which has been cycled to 41,093 in the LMSC Quick-Look I chamber. The significant findings of this review are as follows:

- Only three joints, all of which are "P" contacts, exhibited cracking. In all three cases thick teflon tape had been placed adjacent to those three joints to attach power lead wires on the panel.
- Excluding these joints, 1021 joints were entirely crack-free.
- All I_{SC} - V_{OC} measurements have been within measurement tolerance for the fifteen electrical inspections since the unit went into test.
- It is strongly indicated that vacuum testing alleviates stress corrosion inducing factors that cause micro-cracking.

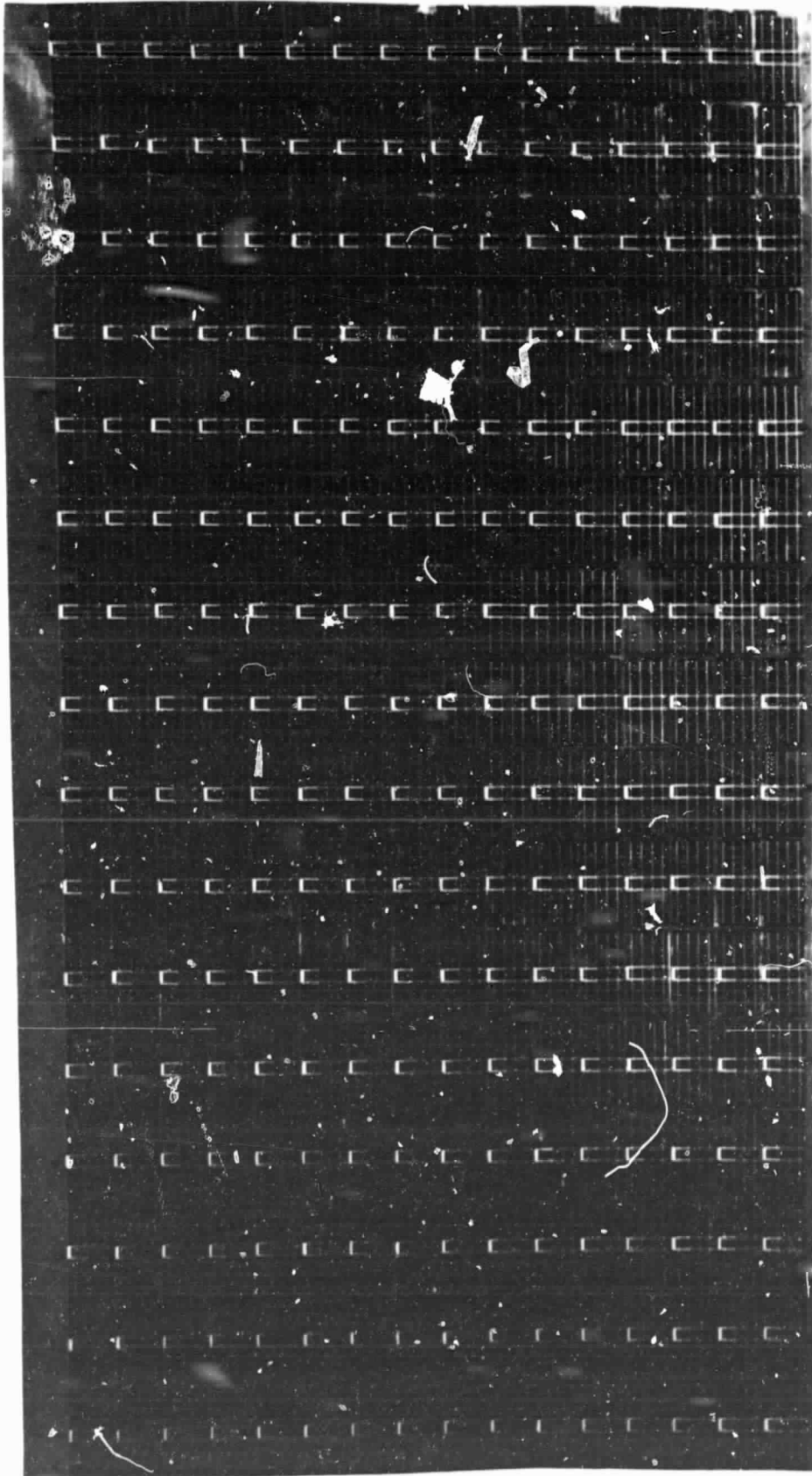


Figure A-2 256 Cell Panel

- It is indicated that vacuum-radiative cycling is more benign than purged radiative convective testing. Vacuum-radiative is more representative of on-orbit conditions. Even though the 256 cell module went through 35°C greater temperature excursion (+10°C and -25°C), joint cracking did not occur except as was explained above.
- Quick-look testing is a valuable screening test for possible life limiting design and material limitations; however, real orbital life is significantly greater as is evidenced by the foregoing investigation.

Description of Solar Cells in the LMSC 96-Cell Panel and the MSFC 256-Cell Panel

The solar cells used for these panels are 2 x 4 cm DWA cells built by ASEC. The dielectric for contact wrap to the rear cell surface was an oxide formed by Chemical Vapor Deposition (CVD). The cells are 8 mils thick, adhesive bond line 2-3 mils thick with 6 mil microsheet covers. The cells are categorized as being Phase I cells in that they were developed and fabricated at ASEC in the same time frame as the 5.9 cm x 5.9 cm DWA Phase I solar cells. The cells contain no BSF and are 2 ohm/cm BSR cells.